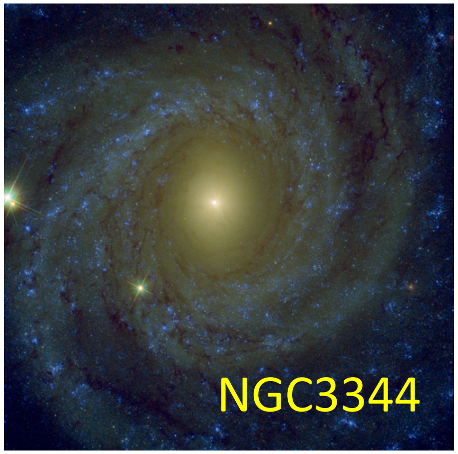


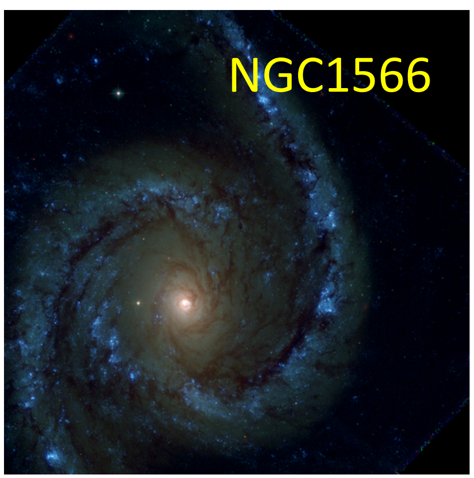
Legacy ExtraGalactic

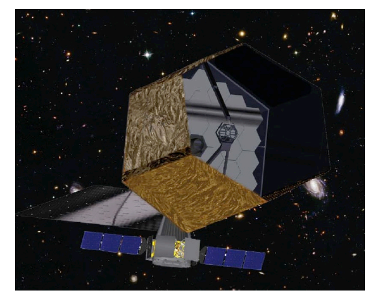
LEGUS

Ultraviolet Survey

Nearby Galaxies: What's Next?

D. Calzetti (Univ. of Massachusetts)



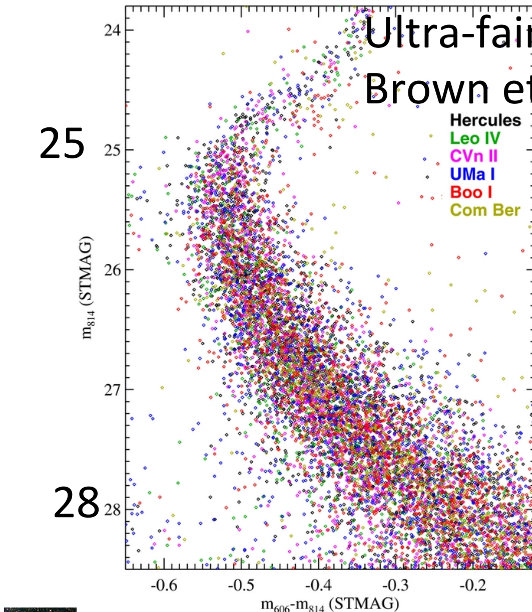


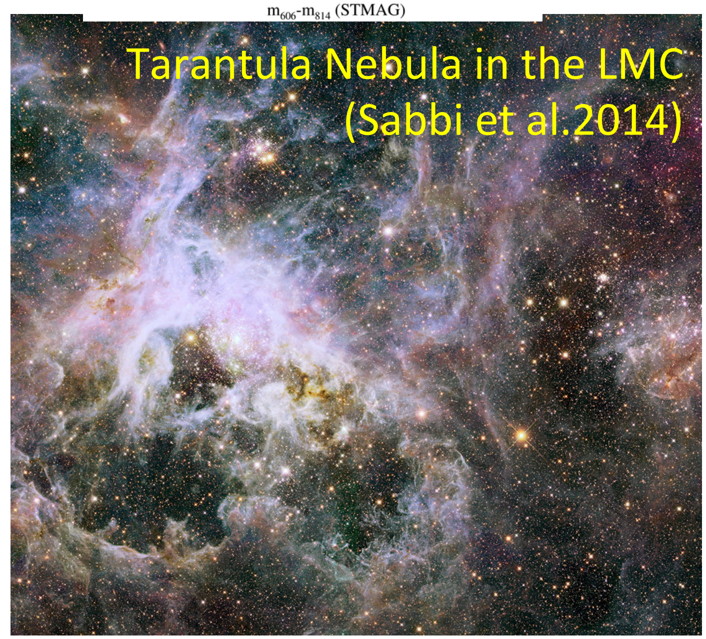
ATLAST Seminar Series,
Hosted by: NASA/Goddard Space Flight Center,
October 07, 2015

Nearby Galaxies: The Hubble Revolution

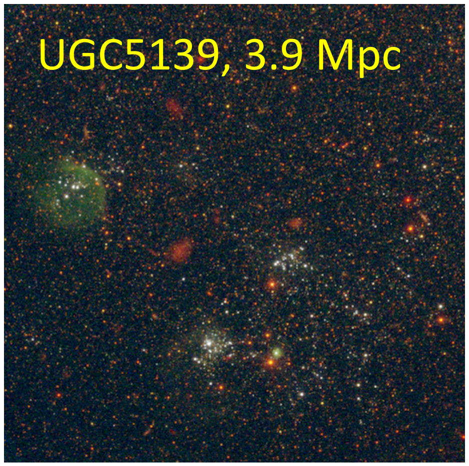
In the past 25 years, Hubble:

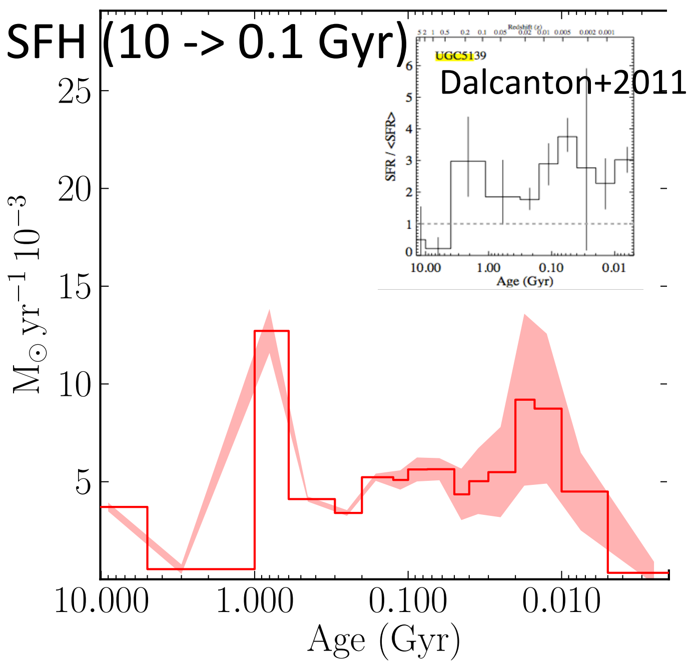
- **Has Enabled** resolution and accurate measurements of individual stars in galaxies beyond the MCs and in otherwise crowded environments (MW GCs, MC star forming regions, etc.) -> SFHs out to 3-4 Mpc
- **Has Enabled** UV measurements of the young structures in external galaxies (stars, clusters, associations, etc.) -> SFRs and Cluster FRs out to ~10-20 Mpc
- **Has Enabled** detecting the ionized gas component and its complex interrelation with the young stars -> SF feedback and chemical enrichment (range of distances, but mostly out to ~20-30 Mpc)

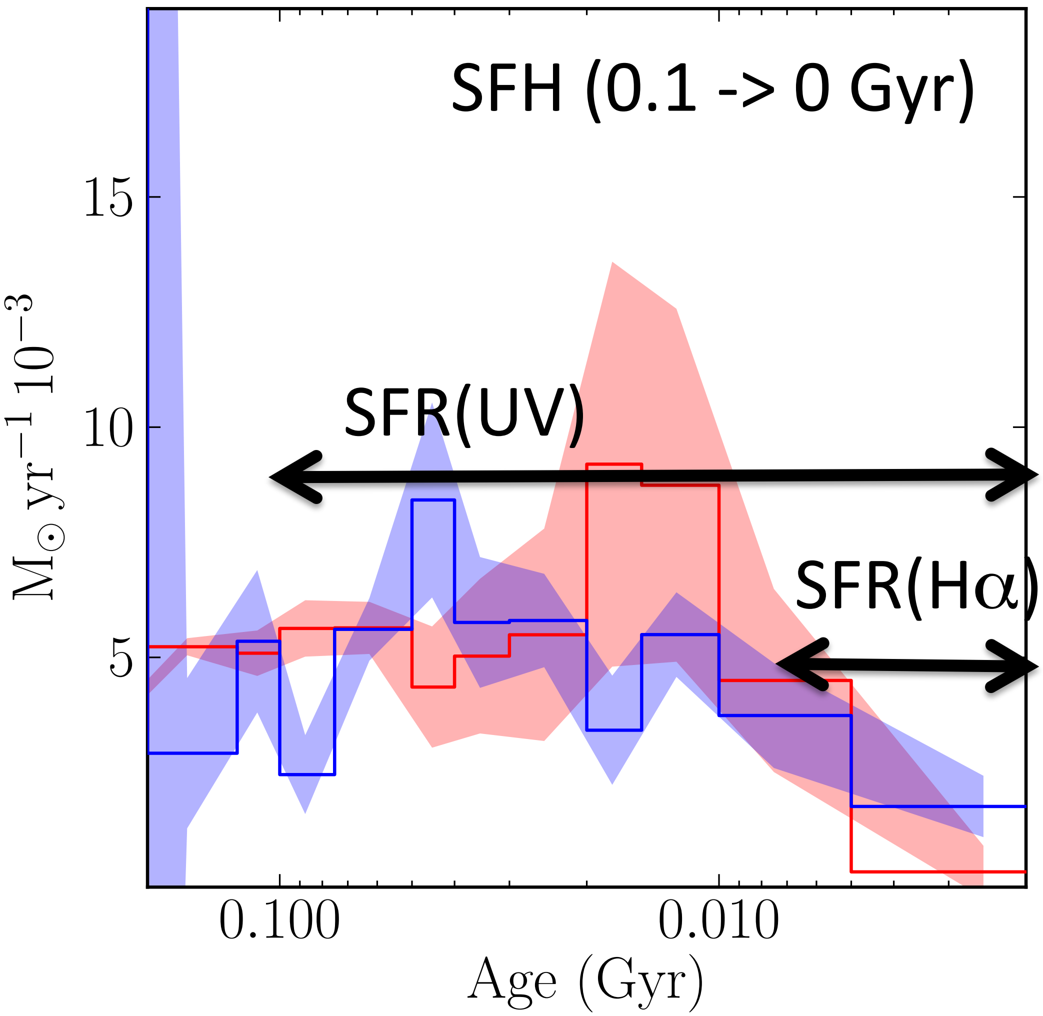




Recent and Past SFHs



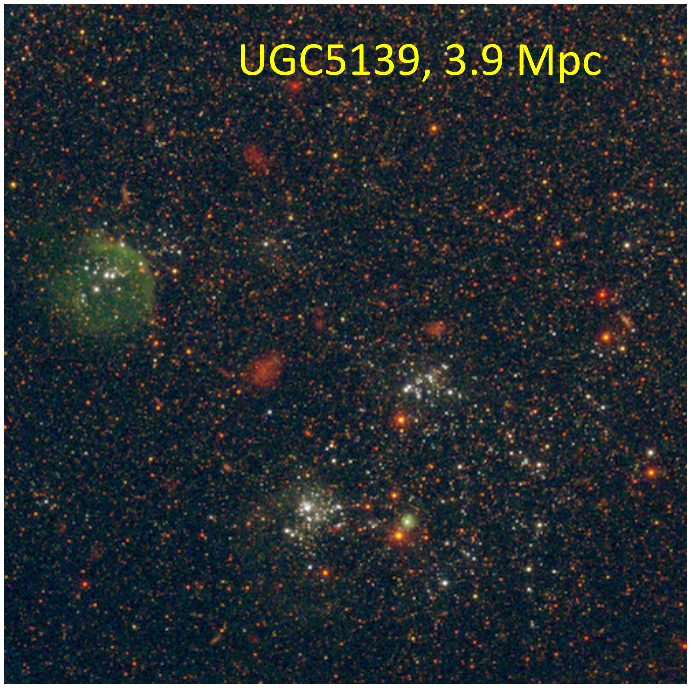




Cignoni et al. (LEGUS)

SFHs and SFRs

- SFRs are based on assumption of constant SFH over the relevant luminosity timescale
- SFR(UV) over ~100 Myr
- SFR(Hα) over ~6-7 Myr



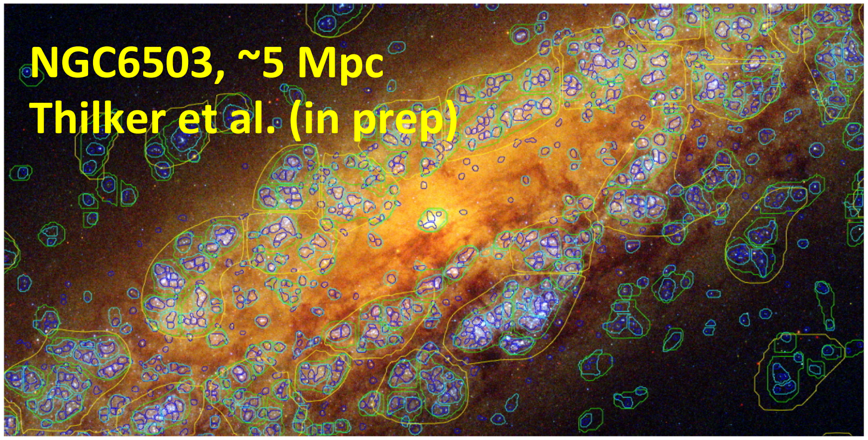
Current SFR in UGC5139 is consistent with ~one 10^4 Mo cluster (or several lower mass ones) having recently formed.

Decrease in recent-past SFR implies:

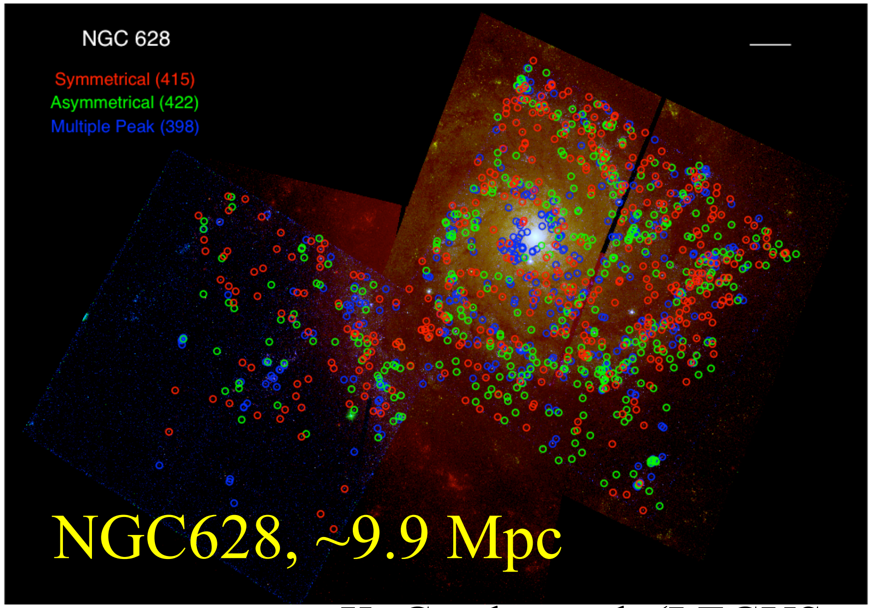
SFR(UV) ~ 2-3 SFR(Hα)

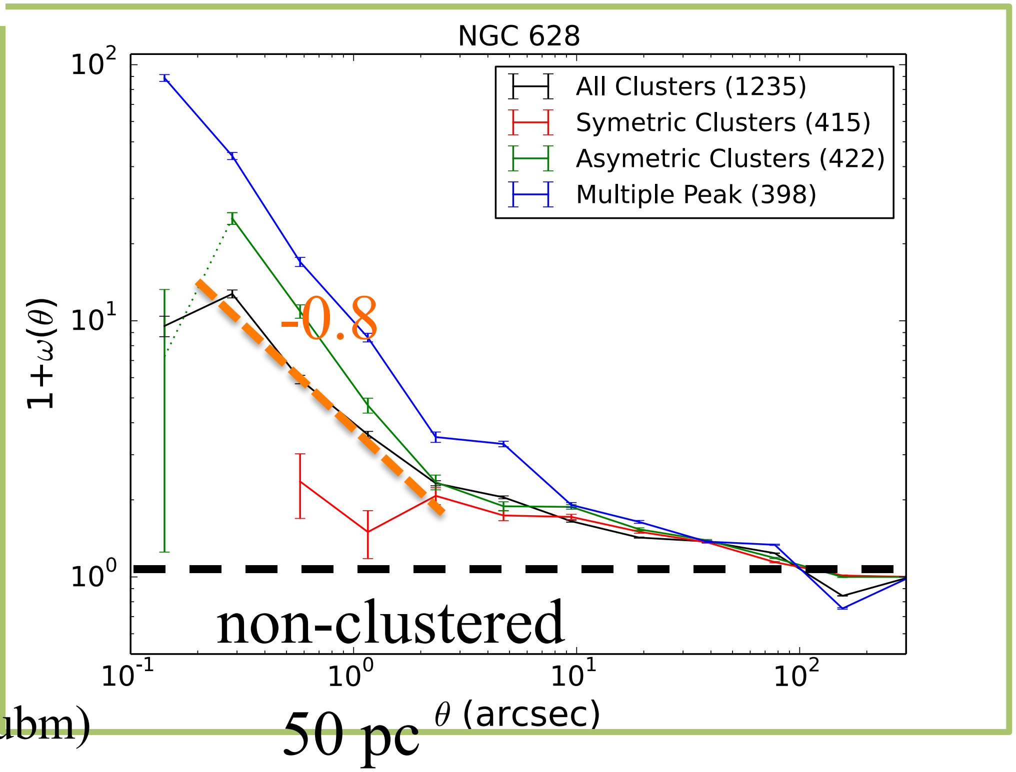
PRELIMINARY

Survival and Dissolution of Clusters



- Clustering studies (stars, clusters) are beginning to demonstrate a `randomization' timescale of young structures around 40-60 Myr
- Seen, so far, in two galaxies: NGC6503 (Gouliermis et al. 2015) and NGC0628 (Grasha et al. subm) – LEGUS key science goal





K. Grasha et al. (LEGUS, subm)

Legacy ExtraGalactic

LEGUS

Ultraviolet Survey

The LEGUS Team

(Cycle 21 HST Treasury)

Red for Senior Advisory Group
Blue for Science, Data Processing, EPO Leads

56 investigators (so far) at 30+ Institutions (US+EU):

D. Calzetti (PI, Umass), J. Lee (Deputy PI, STScI), J. Andrews (U Arizona), A. Aloisi, S.N. Bright, T. Brown, C. Christian, M. Cignoni, K. Levay, M. Regan, E. Sabbi, L. Ubeda, B. Whitmore (STScI), A. Adamo, M. Messa, G. Östlin (Stockholm U), R. Chandar (Utoledo), G. Clayton (LSU), D. Cook, D. Dale (U Wyoming), R. da Silva, M. Krumholz (UCSC), S. de Mink (Amsterdam U), C. Dobbs (UExeter), B. Elmegreen (IBM), D. Elmegreen (Vassar), A. Evans, K. Johnson (UVa), M. Fumagalli (U Durham), J. Gallagher, J. Ryon (UWisc), D. Gouliermis (MPIA), E. Grebel, F. Shabani, (Heidelberg U), K. Grasha, (UMass), A. Herrero, S. Taibi (IAC, Canarias), D. Hunter (Lowell Obs), L. Kahre, R. Walterbos (NMSU), R. Kennicutt (IoA, Cambridge), H. Kim (UT-Austin), D. Lennon (ESA), C. Martin, S. van Dyk (Caltech), P. Nair (U Alabama), A. Nota, L. Smith (STScI/ESA), A. Pellerin (SUNY-Geneseo), J. Prieto (UC de Chile), D. Schaerer (Geneva Obs), D. Schiminovich (Columbia U), D. Thilker (JHU), M. Tosi, E. Sacchi (INAF-Ubologna), A. Wofford (IAP)

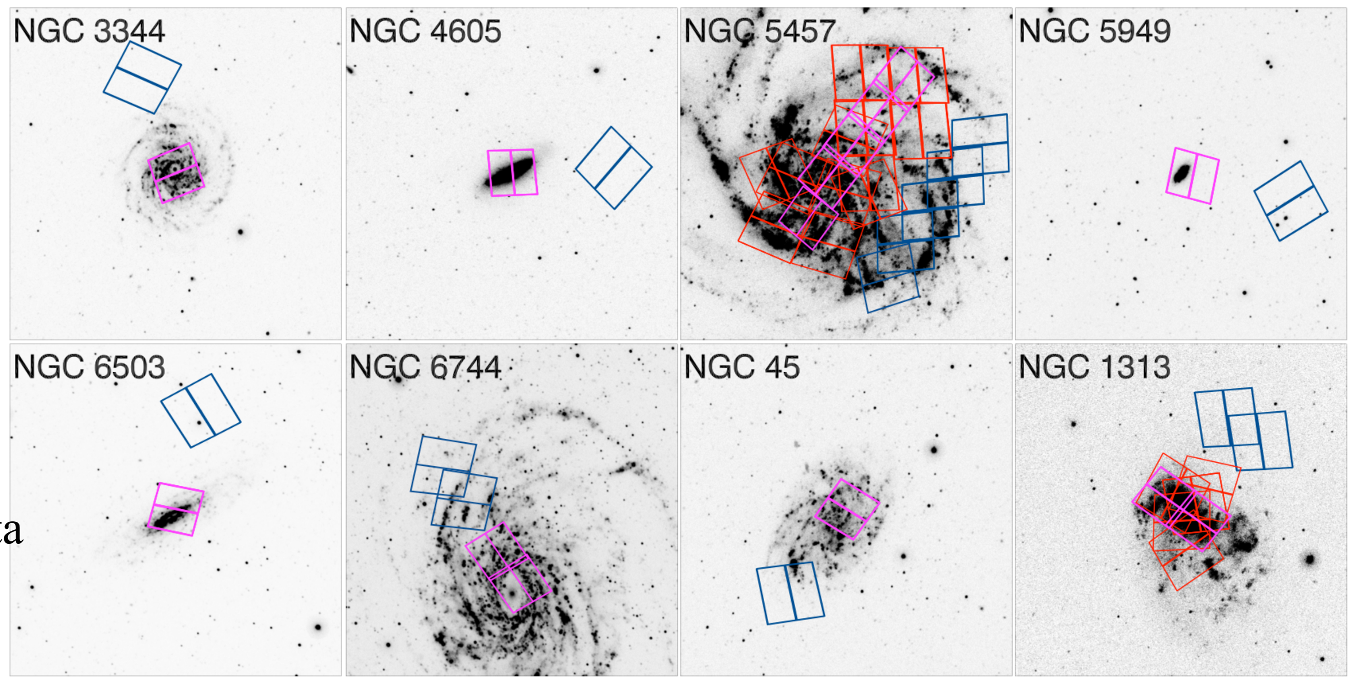
Legacy ExtraGalactic Ultraviolet Survey

The LEGUS Project

legus.stsci.edu C+2015, AJ

- Cycle 21 HST Treasury Program (154 primary + 154 parallel Orbits)
- 50 galaxies, in the range 3.5-12 Mpc, in 126 pointings (63 primary); 100% complete as of Sept 2014.
- Primary: WFC3/NUV,U,B,V,I (5 bands) – leverage the HST Archive as much as possible
- Parallel: ACS/B,V,I

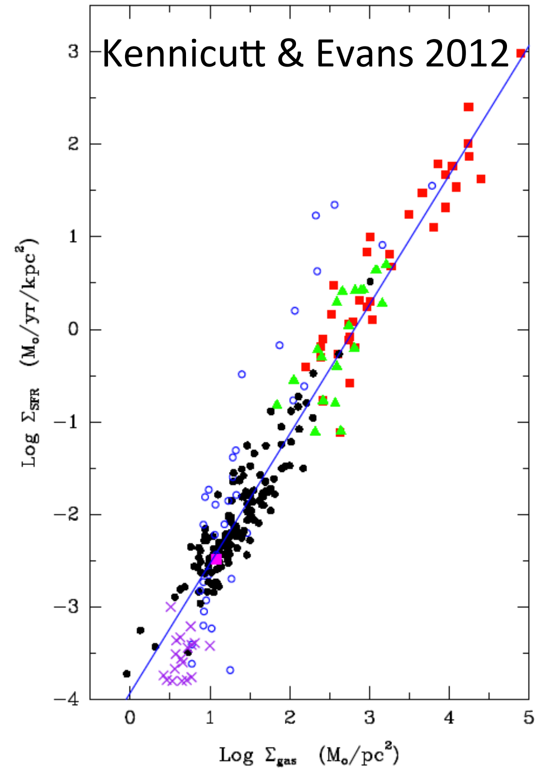
All data are PUBLIC

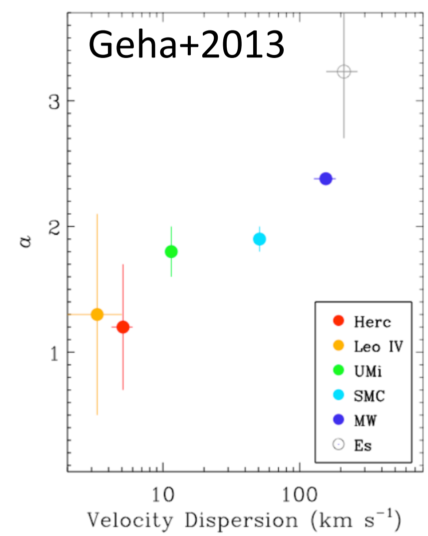


LEGUS footprint=magenta
LEGUS parallels=blue
Archival data=red

The Realm of JWST

- Address the **physical foundation** of the Schmidt-Kennicutt Law (scaling between SFR and gas) via YSOs within 1 Mpc and dust-enshrouded HII regions within ~10 Mpc.
- Investigate the low-end of the IMF via resolved counts out to ~0.5 Mpc (NGC6822). Current evidence gives **2x mass variations** for galaxies.
- SF Histories of galaxies between 200 Myr and 10 Gyr, out to ~6-8 Mpc for `fossil record' studies (~a dozen giant spirals, and at most 1 giant elliptical).
- **Physics** of the Bulge mass – BH mass relation
- **Physics** of dust processing (e.g., PAHs) out to ~10 Mpc and of dust formation (e.g., CCSNe) out to larger distances



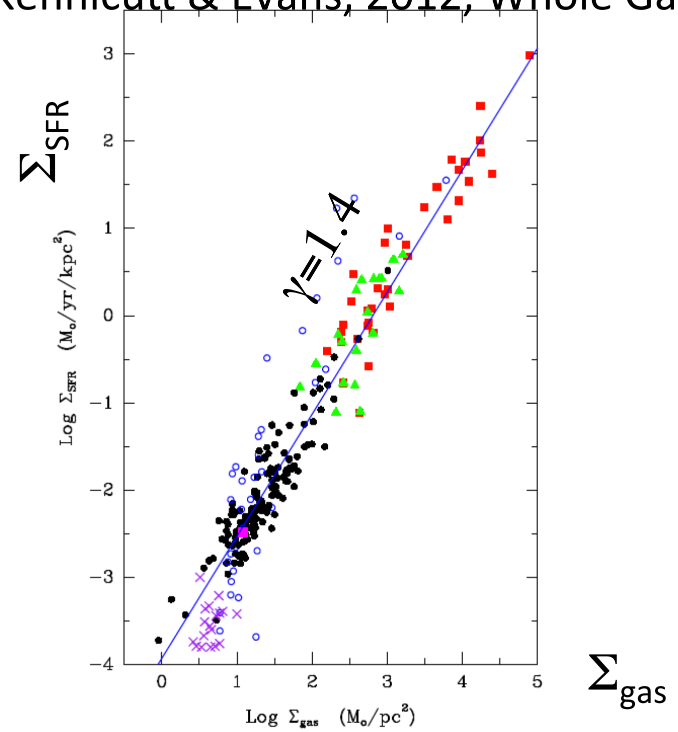


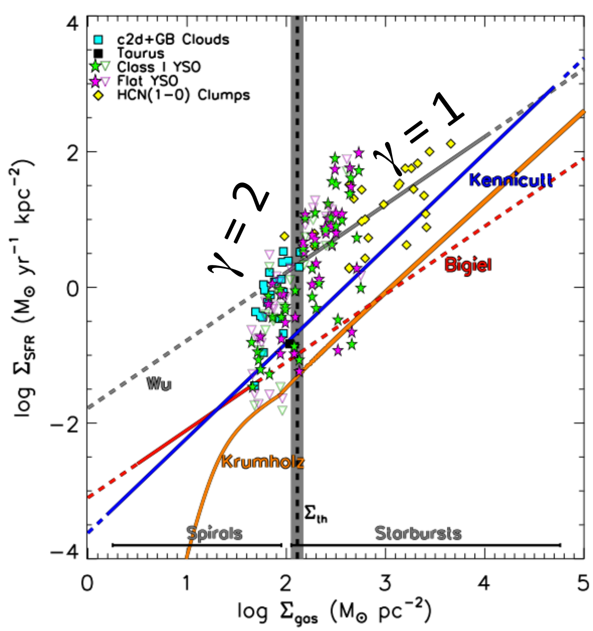
The Schmidt-Kennicutt Law

$\Sigma_{SFR} \sim (\Sigma_{gas})^{\gamma}$, $\gamma=1, \ldots, 2$

The value of γ is connected to the underlying physics of the scaling between star formation and gas (a.k.a. the SK Law).

Kennicutt & Evans, 2012, Whole Galaxies





However, the SK Law does not appear to be `scalable' from whole galaxies to galaxies' constituents (star forming regions, molecular clouds, etc.).

Changing of the dominant physics? (Hopkins+2013)

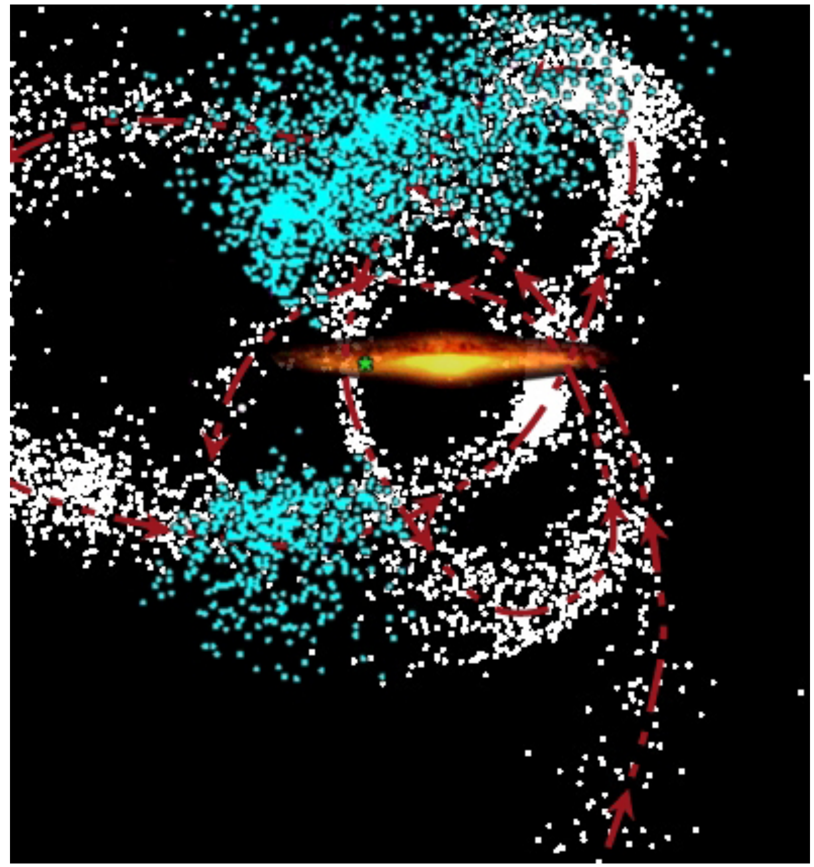
Heiderman et al. 2010, Milky Way Molecular Clouds

The Realm of WFIRST

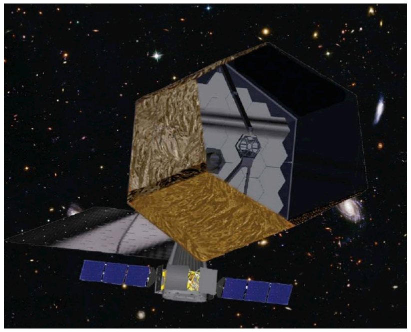
(and Euclid, etc.)

Fossil Galaxy Assembly:

- Mergers of small satellites into larger galaxies is one of the main mechanisms of the hierarchical galaxy assembly in ΛCDM models.
- The signs of these 10:1 mergers survive for multiple Gyrs, in the form of streams, tails, bridges, etc.
- The stellar populations that trace these features can be detected in external galaxies out to ~10-12 Mpc with WFIRST (combination of both FoV and angular resolution), similarly to what is done today from the ground for the MW/MCs/ stream systems



Milky Way Simulation (Rensselaer/ Benjamin A. Willett/Heidi Newberg)



The Questions

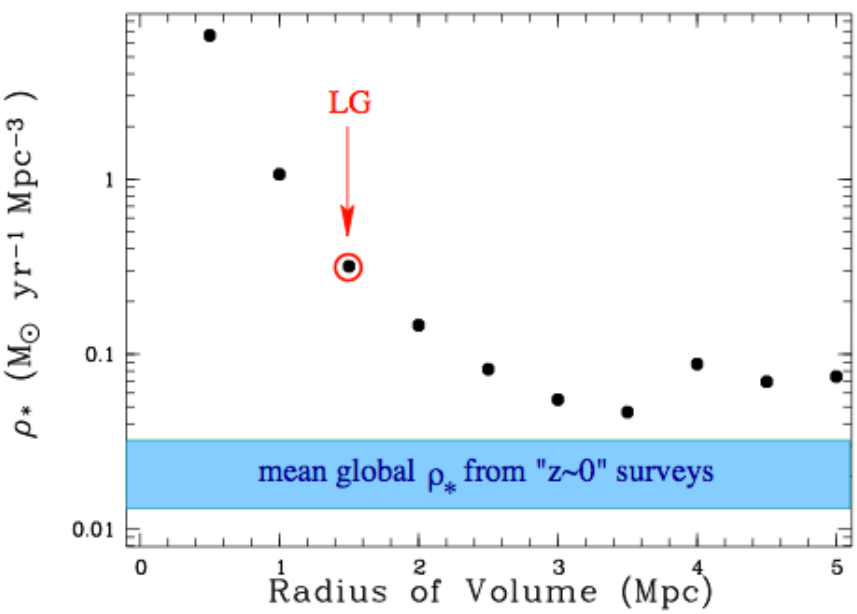
- The Physical Underpinning of the IMF
  - Is the IMF Universal? Low and High End Separately
- The Physics of Galactic-Scale Star Formation
  - Mode(s) of star formation
  - Cluster formation efficiency
  - Cluster-SF links
  - Formation and Erasure of structures
  - Links to dynamical structures, gas structures

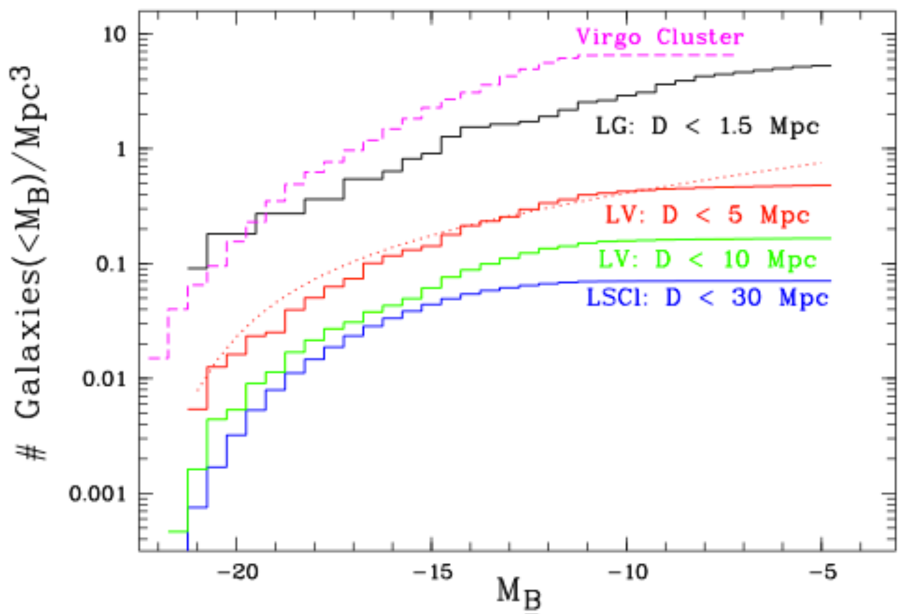
For sake of discussion, I will consider a 12-m UVOIR telescope (5x the angular resolution, 25x the sensitivity of HST). I also need 1-2x the HST FoV.
With this facility:

1. Detect massive stars (>= 10 Mo) out to ~100 Mpc
2. Detect 100 Myr old, 1,000 Mo star clusters
3. Enable derivation of SFHs with 10 Gyr lookback time out to ~20 Mpc

Know Thy Neighborhood - 1

Drozdovsky+2008

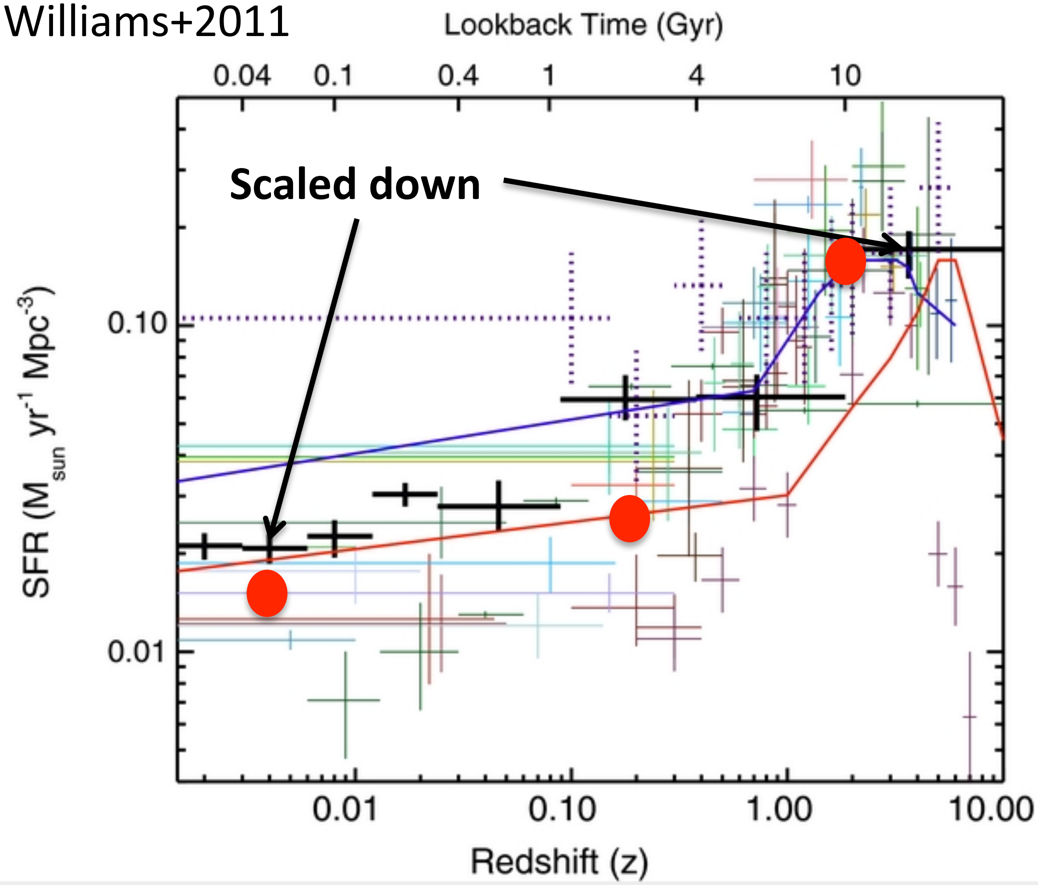




- The Local Universe is over-dense relative to the cosmic average, by a factor of a few, up to at least ~10 Mpc.
- The discrepancy is more noticeable for the LG (local ~1.5-4 Mpc), which departs from the cosmic SFR for the most recent ~4 Gyr (Drozdovsky +2008, Williams+2011)

Know Thy Neighborhood - 2

Williams+2011

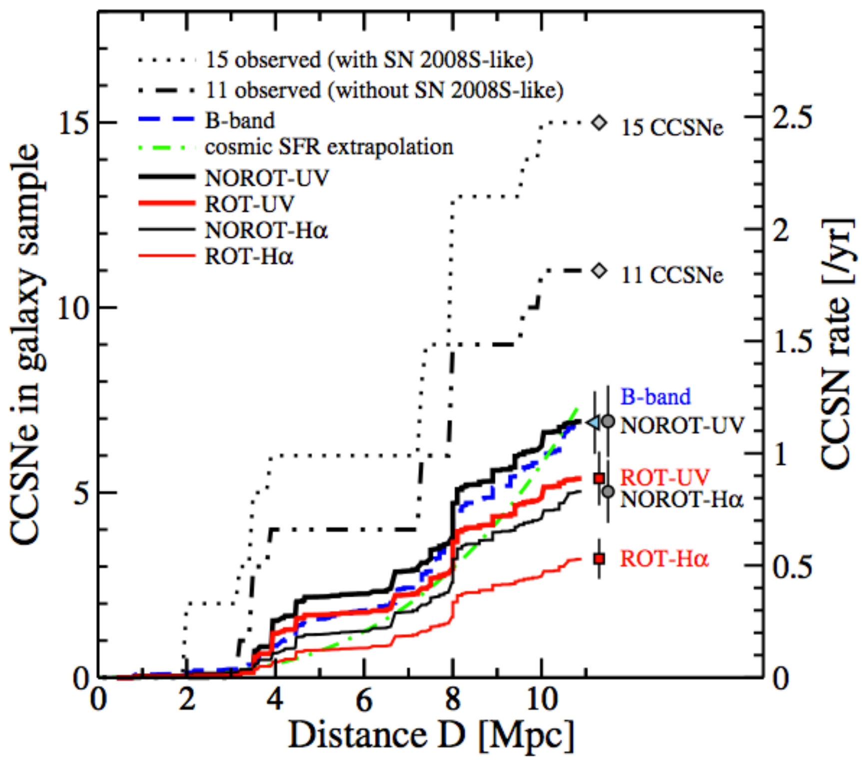


- Even after rescaling:
  - discrepancy (~1.5-2x) between the Local (<4 Mpc) SFH and the Cosmic SFH, over the most recent ~4 Gyr (Drozdovsky+2008; Williams+2011)
- From Madau&Dickinson2014

The Representative Local Volume does not occur before 10 Mpc; need to be up to 100 Mpc, if U/LIRGs are included

Know Thy Neighborhood - 3

Horiuchi+2013



- Within the local 11 Mpc, the CCSNe is higher than predicted by the UV, and even higher than predicted by Hα (Horiuchi+2013, Botticella +2012).
- Within uncertainties, no such discrepancy is observed on cosmic scales (0<z<1, Dahlen+2012).
- The UV-Hα discrepancy is unexpected. Three causes:
  - Upper IMF variations
  - Recent (<200 Myr) SFH issues
  - Ionizing photon escape

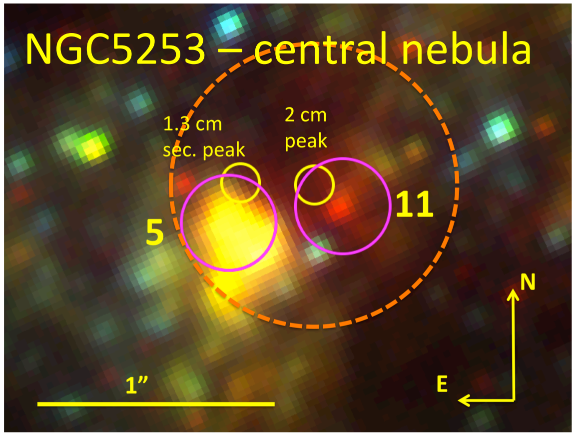
Within the local 11 Mpc, 85% of the SFR is within the 80 galaxies more massive than the MCs (out of almost 500), and 45% of SFR is within the 10 most massive.

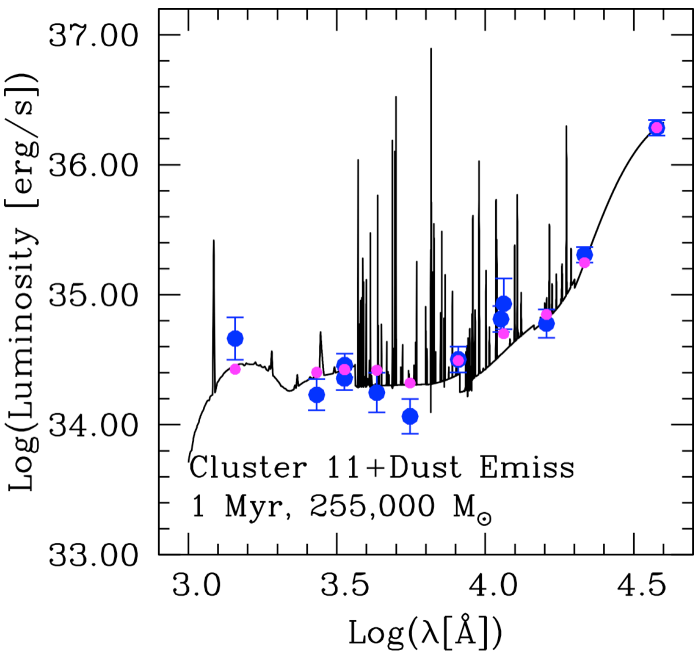
This volume includes only a couple of LIRGs (M82, NGC253), and no ULIRGs; i.e., it does not reflect the high-z Universe, where LIRGs and ULIRGs are common.

Dust-Embedded Star and Cluster Formation

(C+2015, ApJ – LEGUS)

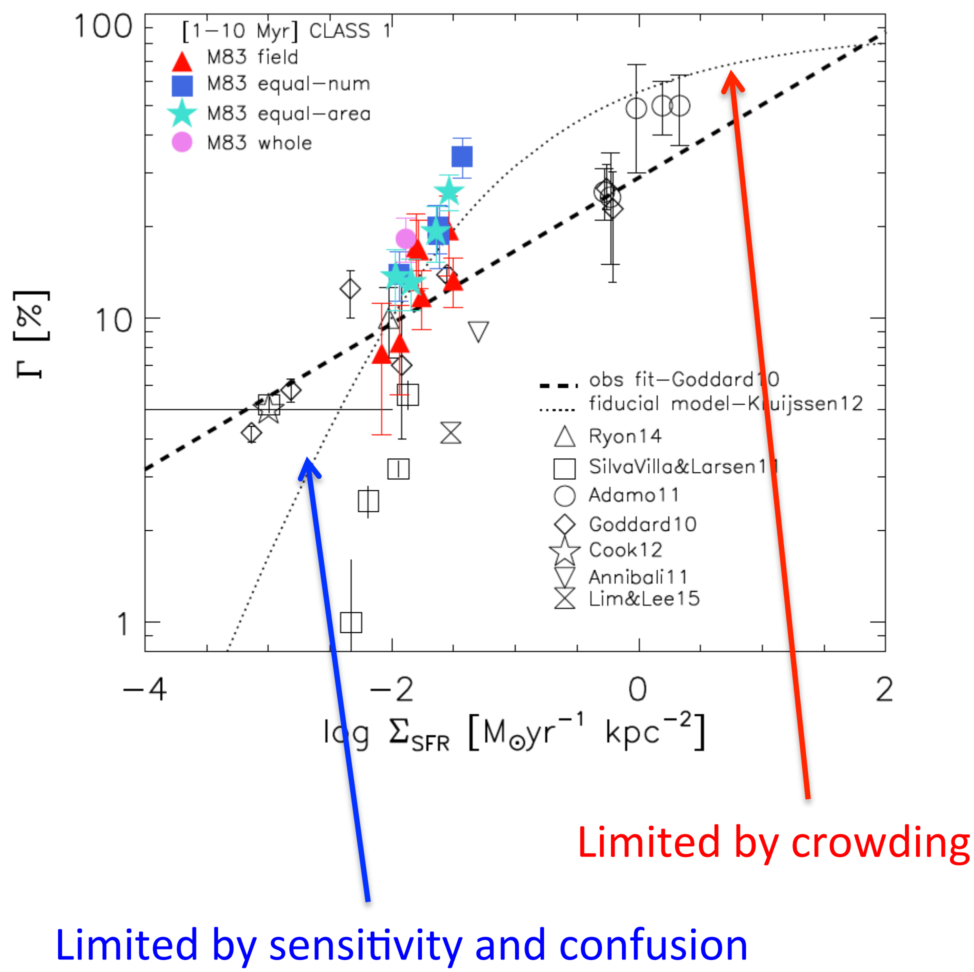
- The UV-detectability of natal clusters is an objective concern.
- NGC5253 (3.2 Mpc) hosts a ~1 Myr old, $2.5\times10^5\ M_o$ cluster embedded in a dust cloud with A_V~50 mag.
- Well detected with HST/UV (both ACS/HRC and WFC3/UVIS)
- Cannot get the mass&age, without UV-optical SED (plus assumption on IMF).





Cluster Formation Efficiency

Adamo+2025, MNRAS



There is tantalizing and mounting evidence that the formation efficiency of young star clusters (defined as the ratio of cluster formation rate over star formation rate) decreases for decreasing SFR surface density.

There are models that account for this as an effect of the declining gas pressure in low SFR systems.

The critical regime is still uncertain and unexplored, because of limitations in both sensitivity and angular resolution both at UV and optical wavelengths.

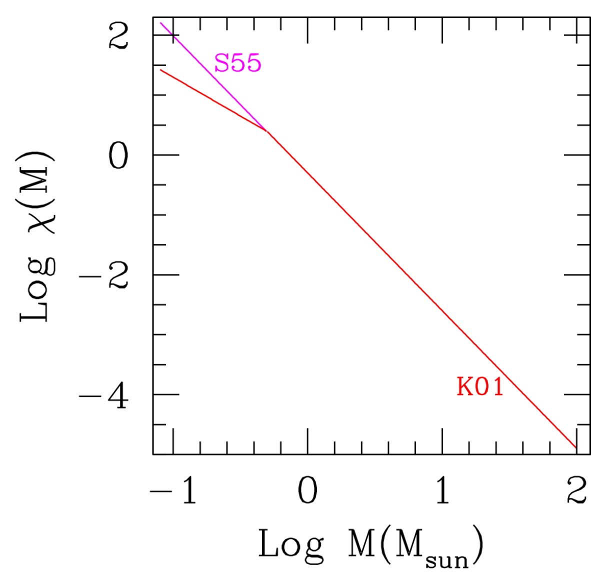
The Stellar IMF

Kroupa (2001) and Chabrier (2003) formulations are roughly equivalent to each other. For Kroupa:

$$\begin{aligned}\chi(M) = dN/dM &= A\ M^{-1.3} & 0.1 \le M(M_\odot) \le 0.5, \\ &= 0.5\ A\ M^{-2.3} & 0.5 \le M(M_\odot) \le 120\end{aligned}$$

Variations at the high IMF end crucially affect SFRs:

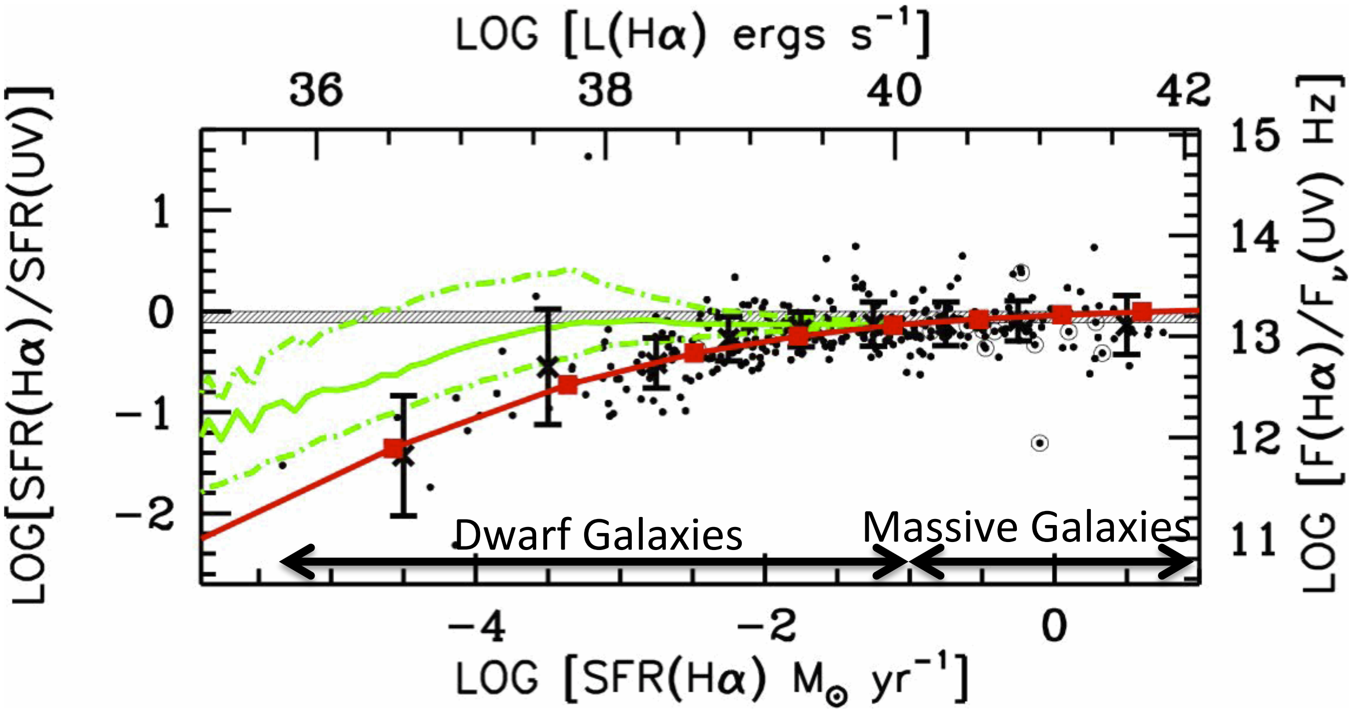
$$\mathrm{SFR}(\lambda) = \mathrm{C}(\mathrm{IMF,SFH})\ \mathrm{x}\ \mathrm{L}(\lambda)$$



Variations at the low IMF end crucially affect masses.

JWST can reach out to 0.5 Mpc; 12m UVOIR could reach out to ~1-2 Mpc (depending on crowding-faintness interplay), Starts to include at least Andromeda and Triangulum.

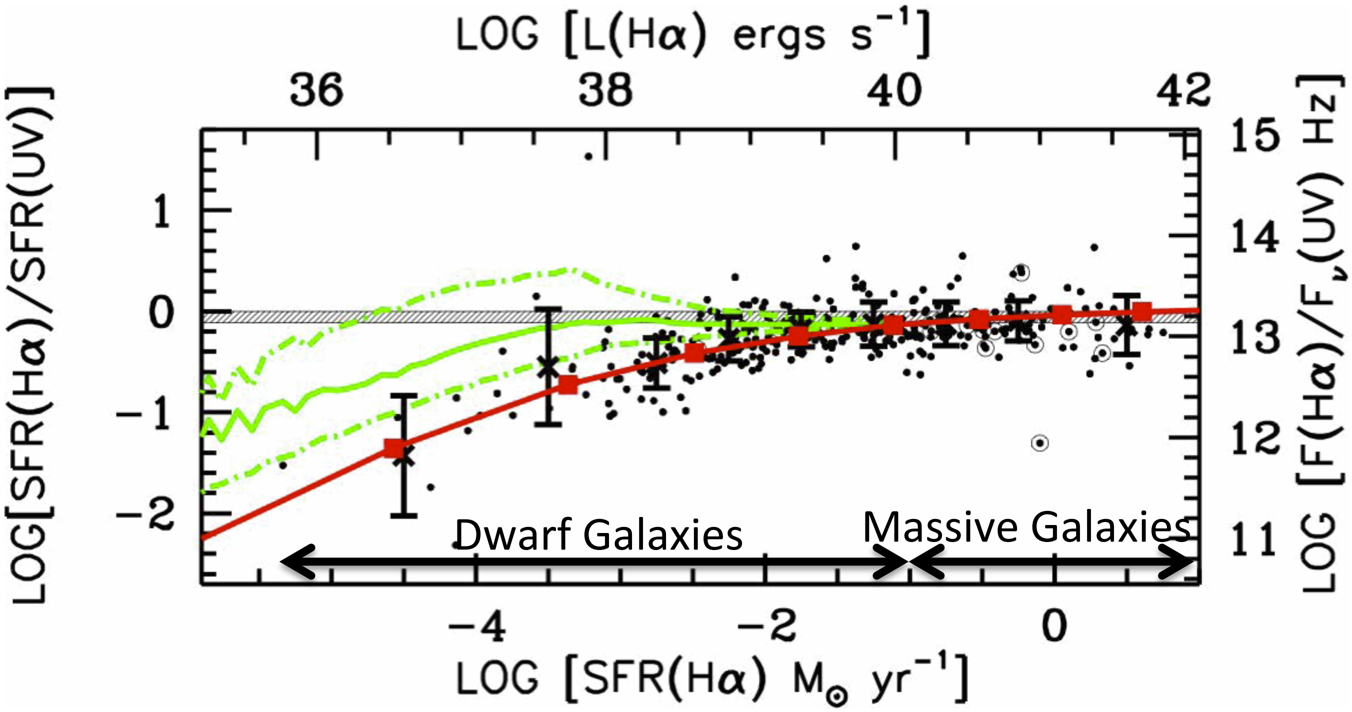
Massive Stars IMF



Lee et al. 2009

- The upper end of the stellar IMF impacts:
  - SFRs at all cosmic distances
  - Energy input into the ISM/IGM (feedback/outflows)
  - Metal enrichment/abundance ratios

Testing the Massive Stars IMF



Lee et al. 2009

- Problems with integrated light from galaxies:

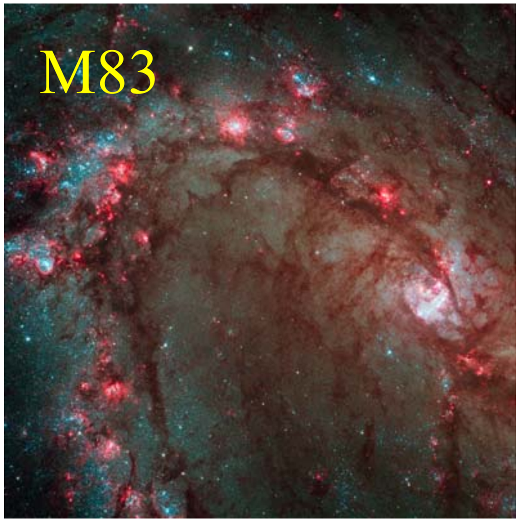
1. SFH/IMF degeneracy
2. Loss of ionizing photons

- Problems with resolved stars studies:

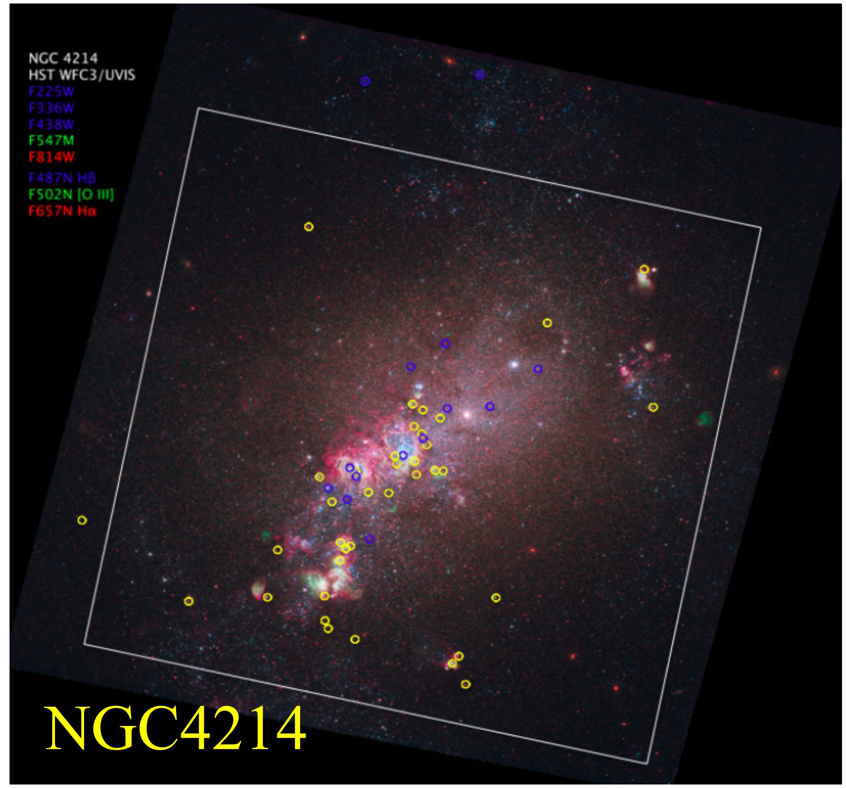
1. Cannot push observations beyond MCs

Test the IMF with Young Star Clusters

C+2010, Andrews+2013, 2014



WFC3-ERS:
BB+NB HST imaging



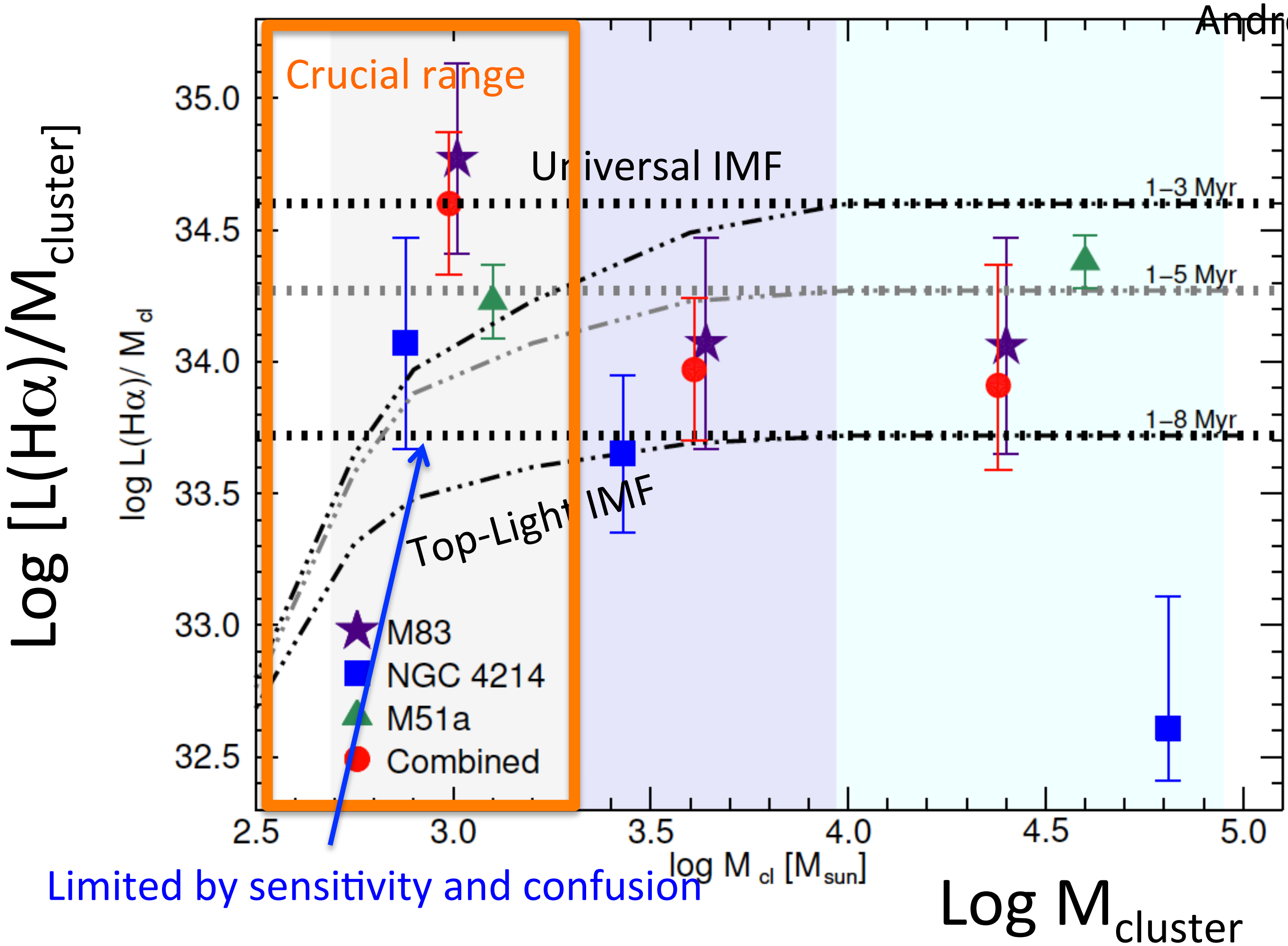
Clusters are simpler populations than whole galaxies, and can be resolved out to ~100 Mpc with 12m UVOIR telescope

Ages, masses, extinctions using LEGUS-like approach (broad/medium band photometry). Additional information required: extinction-corrected ionizing photon flux: Hα + one other recombination line.

Optimal approach: multiobject UV-optical spectroscopy

Massive Stars IMF – with Clusters

Andrews et al. 2013, 2014

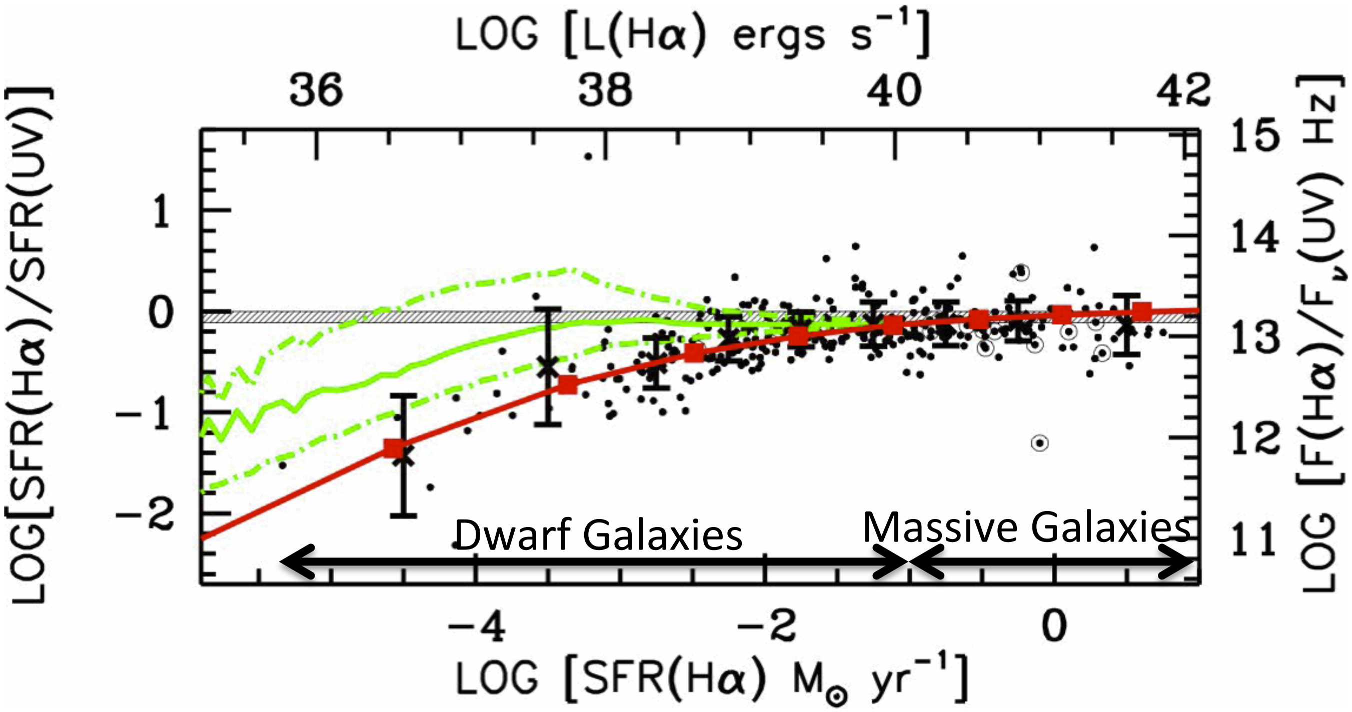


The data show average values per mass bin for star clusters in the listed galaxies.

Cannot use IR data, because of IMF stochastic sampling

The universal IMF is preferred at the 2-σ level only. Need to get tighter constraints using a larger number of star clusters in dwarf galaxies.

Massive Stars IMF



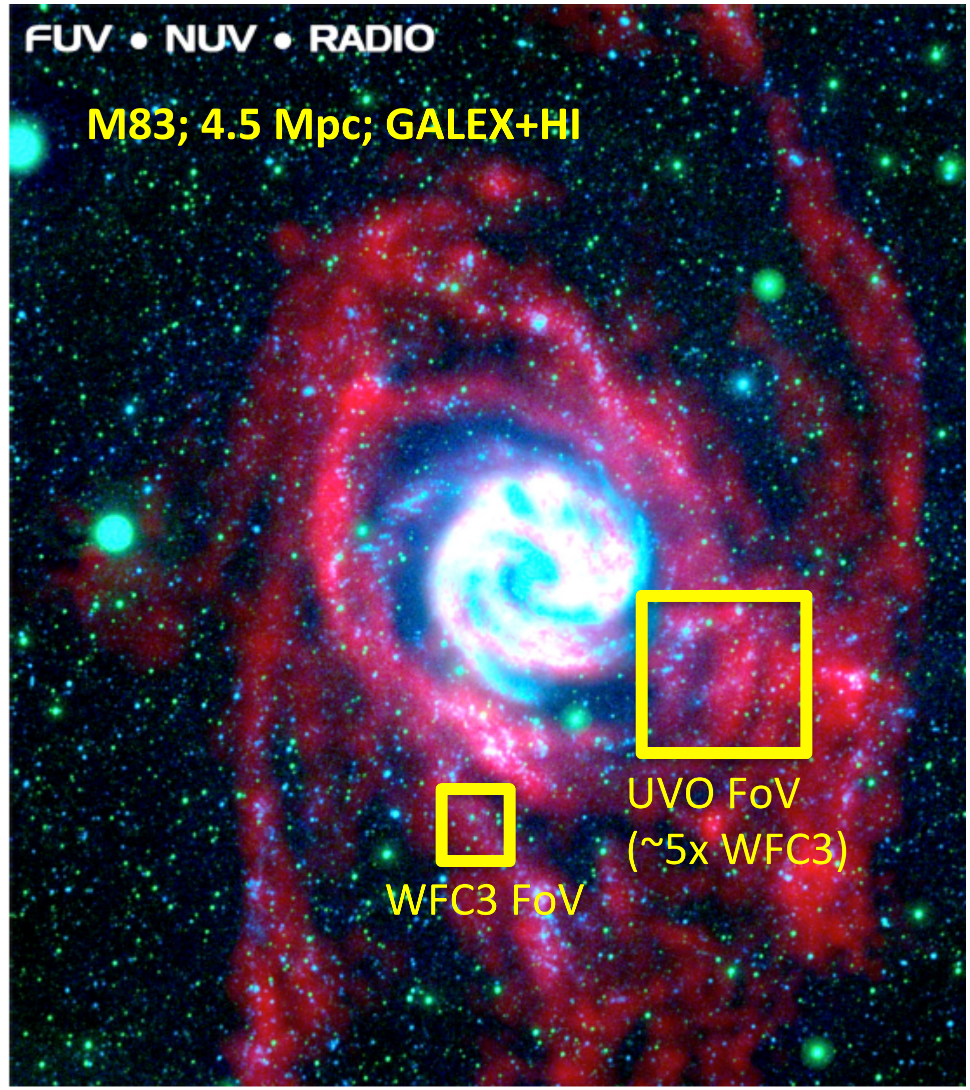
Lee et al. 2009

Problems:
1. SFH/IMF degeneracy
2. Loss of ionizing photons

- The upper end of the stellar IMF impacts:
  - SFRs at all cosmic distances
  - Energy input into the ISM/IGM (feedback/outflows)
  - Metal enrichment

Outer Disk Physics

- Galaxies are far more extended than their bright disks, in stellar populations and gas content.
- Regions with extreme conditions of density, pressure, metal enrichment, dust content, response to feedback.
- Outskirts are dynamically `quiet': imprints of structures persist for many Gyrs – testbeds for:
  - Modes of star formation
  - Upper IMF universality
  - Star cluster evolution and internal processes
- Key requirements: UV (SFH<200 Myr) +efficiency (FoV+sensitiv.)



Thilker et al. 2007

Conclusions

- There are at least two areas of investigation in Nearby Galaxies that will reach closure with a large (~12m) UVOIR facility:
  - The Physical Underpinning of the IMF
    - Is the IMF Universal? Low and High End Separately
  - The Physics of Galactic-Scale Star Formation
    - Mode(s) of star formation
    - Cluster formation efficiency
    - Cluster-SF links
    - Formation and Erasure of structures
    - Links to dynamical structures, gas structures